Introduction

Underbalanced Drilling (UBD) is a modern drilling technology whereby the pressure in the wellbore is purposely maintained below the formation pressure. That minimizes drilling fluid invasion into the reservoir, substantially lessening the chances of formation damage and improving productivity. UBD also aids recognition of productive zones, facilitating real-time decision-making during the drilling operation itself.[1]

The technique originated in the 1950s to salvage many a drilling job from the drawbacks posed by application to fractured and depleted reservoirs. With time, focus shifted to minimizing formation damage until better equipment was developed, the likes of rotating control devices with inducted real-time monitoring systems, made UBD work efficiently and safely. Today, UBD finds widespread applications, including complex wells, such as horizontal and directional wells, and where traditional overbalanced drilling (OBD) techniques can damage the formation or create operational inefficiencies.

UBD applies in cases where any consideration of reduction of formation damage, enhancement of well productivity, and increase in operational efficiency is of note, notwithstanding, under OBD conditions there is good control on high-pressure reservoirs, unlike in UBD applications where, under depleted or fractured formations, costs can go down considerably and the integrity of a reservoir is maintained.[2]

The dissertation will explore the central tenets of UBD and compare them with OBD to appreciate where these methods stand from the viewpoint of strengths, challenges, and applications. The chapters will cover the following:

1. Techniques of UBD Including gas injection, foam-based fluids, and aerated muds.

2. Equipment and Rig Modifications– Discussing specialized tools and their adaptations.

3. Advantages and Challenges Highlighting the benefits and operational issues.

4. Applications and Case Studies – Considering where UBD performs better than OBD.

5.Future trends-innovations in UBD techniques and equipment.

This structured comparison will make it possible to appreciate UBD from the current context of petroleum drilling operations.

Gases for Air/Gas Drilling :

Natural Gas Drilling :

for Drilling Natural gas is an excellent choice for air/ gas drilling due to its capability to minimize erosion, help downhole fires upon piercing hydrocarbon zones, and exclude the threat of fire blowback through the blooey line. still, unlike nitrogen, natural gas forms combustive fusions when exposed to the atmosphere, adding the threat of face fires. This requires modified operating procedures compared to air drilling. generally, natural gas drilling necessitates access to a near gas force channel, with parcel or channel gas available in sufficient amounts for operations. [2][7][8]

Air Drilling :

Air is the most generally used gas in air/ gas drilling due to the vacuity of compressors and boosters designed for this purpose. Dry air is generally employed in perpendicular, small- periphery wellbores without sour gas or anticipated downhole fires. still, dry air drilling faces limitations, similar as water flux, downhole fires, and wellbore insecurity. The entry of water into the well during drilling can produce significant challenges that frequently count its use. [2][15][3]

Nitrogen in Drilling :

Nitrogen serves as a safer volition to air in conditions where hydrocarbon feasts might mix with the drilling fluid, as these fusions arenon-flammable, reducing the threat of downhole fires. Nitrogen is particularly profitable when drilling with mist in the presence of acid feasts like CO_2 or H_2S, piercing condensate zones, or dropping out oil painting- producing conformations. Like air, nitrogen effectively lifts slices and liquid inrushes but is limited by its advanced cost.[7][4]

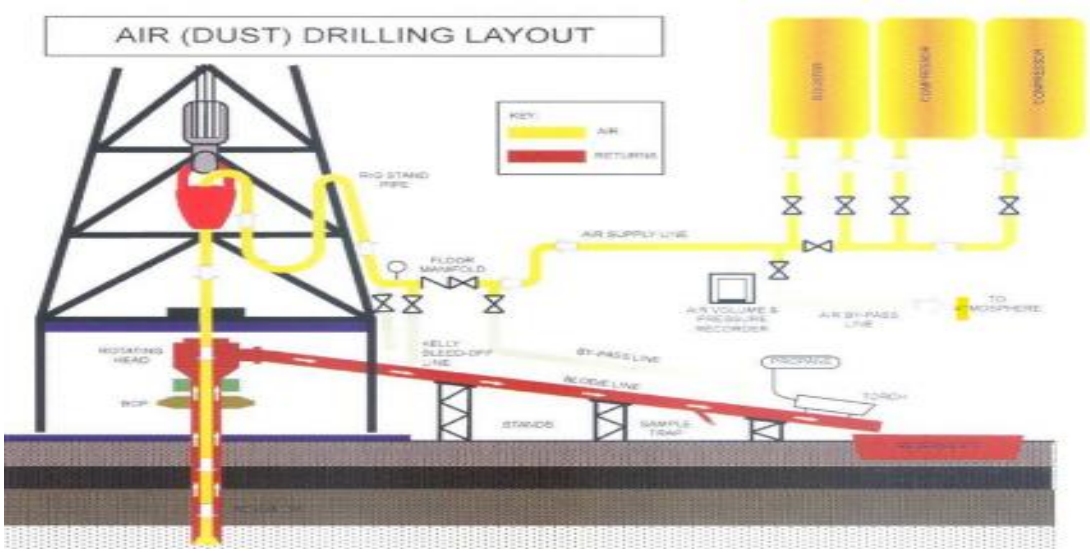


Fig. 1: Aerated fluid drilling layout

Overview of Air/ Gas :

Drilling Air/ gas drilling encompasses the use of air, nitrogen, or natural gas (rather methane) as the gassy phase in underbalanced drilling(UBD). While air drilling is common, it's prone to erosion and implicit downhole fires, egging nitrogen to come the favored gas for UBD due to its safety advantages. Despite the differences between air and gas as drilling fluids, the term" air/ gas drilling" is frequently used interchangeably to describe their analogous functional characteristics [2][8]

Advantages of Air/Gas Drilling [2][7]

1. Increased rate of penetration (ROP).
2. Shorter drilling time and reduced drilling costs.
3. Longer bit life with lighter bit weights.
4. Minimum formation damage.
5. Healing of hidden productive zones due to skin damage.
6. On-line production testing during drilling.
7. Increased production from open-hole completions.
8. Reduced probability of lost returns in depleted or naturally fractured reservoirs.

Limitations of Air/Gas Drilling

Water Inflows:

- Results in bit balling and the formation of mud rings which tend to stop drilling operations and inhibit adequate cleaning of the hole.
- This can include a switch to either mist/foam or sealing of water-producing zones.[7][8]

Downhole Fires

- They occur due to the ignition of hydrocarbons in the presence of oxygen.
- Risks increase with the rise of fuels: oxygen, hydrocarbons, and ignition from compression.[8]

Instability of the Wellbore:

- Low wellbore pressure; weak formation who need high pressure probably should be stabilized.
- Water inflow in some shales may also pose stability concerns.[7]

Corrosion:

- Water containing high oxygen causes harmful corrosion.
- This may be mitigated by either nitrogen or inhibitors of corrosion.
- Sizes of Cuttings:
- Larger cuttings may be carried shallowly; however, they tend to break into smaller fragments or dust based upon limestone and/or depth later down the operation.[7][2]

Cutting Size in Air/Gas Drilling :

- A long chip about 0.64 cm (0.25 in.) is manufactured by the drill bits, through scattering surrounding smaller fragments or dust.
- Larger chips are easily blown out of shallow holes.
- In deeper holes, turbulence, collars, and drill pipe break cuttings into smaller fragments.

- Increased depth leads to further particle breaking down, rendering the cuttings into very small dusts.[7][8]

Mist Drilling:

- Mud Composition: Mixtures of gas with small amounts of water (under 2.5% water), that forms a mist wherein gas is the continuous phase, while water is dispersed like independent droplets.
- Mist Formation: Water treated with foam agent is pumped into the compressed airstream before entering the drill string.
- Gas Use: The gas is circulated at a high velocity to lift cuttings and clean the hole; however, it is less efficient than viscous fluids in lifting cuttings.
- Circulation Limitation: The fluid remains as a mist during its entire circulation trip.[13][15]

Limitations of Mist Drilling:

- Air Compression: Would generally require a 30-40% increase in the injection of air, which will also increase the overall operational costs.
- Waste Water Disposal: The water injected cannot be recycled, meaning wastewater disposal can cost more than 6 S/m, not counting any chemical treatment additives.

- Well-bore Instability:

Mist drilling does not improve wellbore stability during the time of mechanical instability. The increased wellbore pressure and gas flow rate

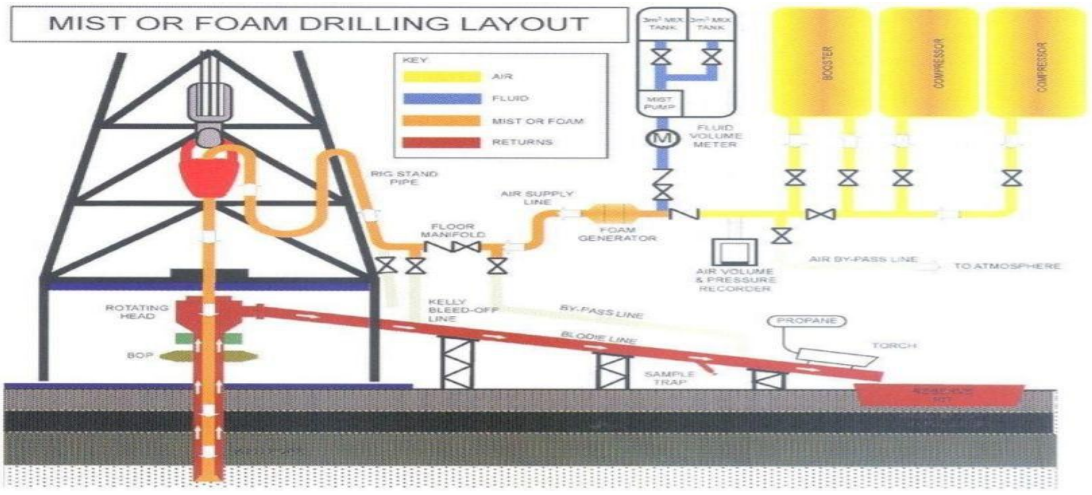


Figure 2: Mist or foam drilling layout

may actually heighten the erosional potential or cause chemical instability particularly at water-sensitive shales.

- Corrosion:

Oxygen concentration in the aqueous phase of compressed air can cause very rapid corrosion of downhole equipment; corrosion inhibitors must be used to protect the equipment.

Foam Systems

Foam drilling is formed with foam created by using water and gas along with surfactants to stabilize the liquid film surrounding gas bubbles. Foam is made of 97% gas and 3% liquid at the surface. Two types of foam exist in underbalanced drilling: stable foam, which merely uses a surfactant as a binder, and stiff foam, which uses bentonite or other polymers together with surfactants.[4]

- Gases and Liquids Used

Usually, air is employed as the gas source for foam, but nitrogen, natural gas, or carbon dioxide can be used as well. Acid gases, like hydrogen sulfide, should be avoided due to adverse effects on foam stability. Fresh water is by far the most economical liquid for foam because it works very well with surfactants. Brine and oil can be used but require specialized surfactants or foam break down may occur rapidly.[1]

-Efficiency of Cuttings Transport

Foam's high effective viscosity makes it unique for transporting cuttings, including large ones. Even after circulating stops, foam continues to expand, lifting cuttings out of the well. Stiff foams, with higher viscosity, are especially efficient in large-diameter holes or when annular velocities are low; thus, they are suitable for economically drilling large holes with water influx but with little gas influx.[1]

- Foam Quality

Foam quality can be defined as the gas percentage in the foam. The acceptable range for good foam is from 55-97%. The carrying capacity increases with increasing foam quality. Above this point, the foam tends towards mist if it

exceeds 97%. The foam quality also varies with depth, as the pressure should compress the gas which is responsible for decrease in foam quality.[1]

Foam Drilling Application

1. Minimized Lost Circulation: Foam reduces lost circulation by decreasing bottom-hole pressures either by fountain-head suppressing some lost zones through expanding foam bubbles, as opposed to solids.
2. Well Protection: Foam reduces the possibility of damaging the reservoir, by inhibiting the ingress of solids or filtrate into the formation, thus improving reservoir re-establishment.
3. Differential Sticking Avoidance: Foam avoids differential sticking primarily through its effect on minimizing the solids content, creating a condition that avoids pressure imbalances.
4. Faster Rates of Drilling: The continuous removal of cuttings and a decrease in hydrostatic pressure increase the penetration rate.
5. Hole Cleaning Capability: Due to its excellent transport characteristics, foam ensures effective cutting removal and suspension at lower annular velocities.
    a. Although Foam Drilling Has Its Limitations :
6. Corrosion: Downhole equipment can corrode due to the foam's O2. This issue can be solved through the addition of inhibitors and oxygen scavengers.
7. Wellbore Instability: While foam's cuttings transport efficiency reduces erosion, it does not provide sufficient borehole support in weak formations.
8. Mechanical Instability: Foam might increase the pressure in the borehole; however, a more significant decrease isnor does it stabilize weaker rock formations.
9. Chemical Instability: Inflows of formation water can modify the formulation of foam, possibly deleteriously affecting water-sensitive shales.
10. Downhole Ignition Fires: In horizontal wells, foam separation can lead to the formation of air-continuous phases, thus creating a fire hazard.
11. Foam Disposal: Environmental restrictions render foam disposal complicated. Often, a defoaming system is required to recycle foam.[1]

Gasified Fluids system

Gasified fluids, that is nitrified or aerated fluids, are gas-liquid mixtures used to reduce the density of fluids. Gas is injected into the fluid system to replace part of the liquid and lighten the fluid column. This is often done to maintain bottom-hole pressure (BHP) just below pore pressure, but above wellbore-stability pressure. The gas can be injected at the surface through the drillpipe or downhole into the annulus. Common gases include air and nitrogen, and liquids used include water (fresh or salty), oil, condensate, or drilling mud. Once the gas-liquid mixture reaches the surface, it separates easily into its respective phases.[7]

- Optimization and Operations

Gasified systems are optimized for effective hole cleaning and pressure management during underbalanced drilling (UBD). The fluid properties, including viscosity, gel strength, and velocity, have to be controlled to ensure stability and efficient cuttings removal from the annulus. The compressibility of the gas phase factors into system performance: the gas volume changes with temperature and pressure. An ideal gas-to-liquid ratio of 5:1 to 40:1 (or foam quality of 80%-97.5%) should be maintained. Gas can be introduced through the drillpipe, a parasite string, or via other injection methods. Gasified systems help in preventing lost circulation, minimizing the formation damage, avoiding differential sticking, and increasing the rate of penetration by reducing both the filter cake and filtrate entry into the formation.[7]

- Limitations of Gasified Fluids

The major limitation of gasified systems, however, is their instability. Once created, a fluid column on storage in the annulus must remain steady without any interrupts within the system. In case of interruption of operations, gas-liquid separation occurs in the annulus, generating slugs of pure liquid when circulation is resumed. This problem can be countered by way of introducing some gas slugs to counteract liquid slugs. The management of pressure and volume transients themselves during operations will enhance the operational ability of a system requiring special equipment for that.[7]

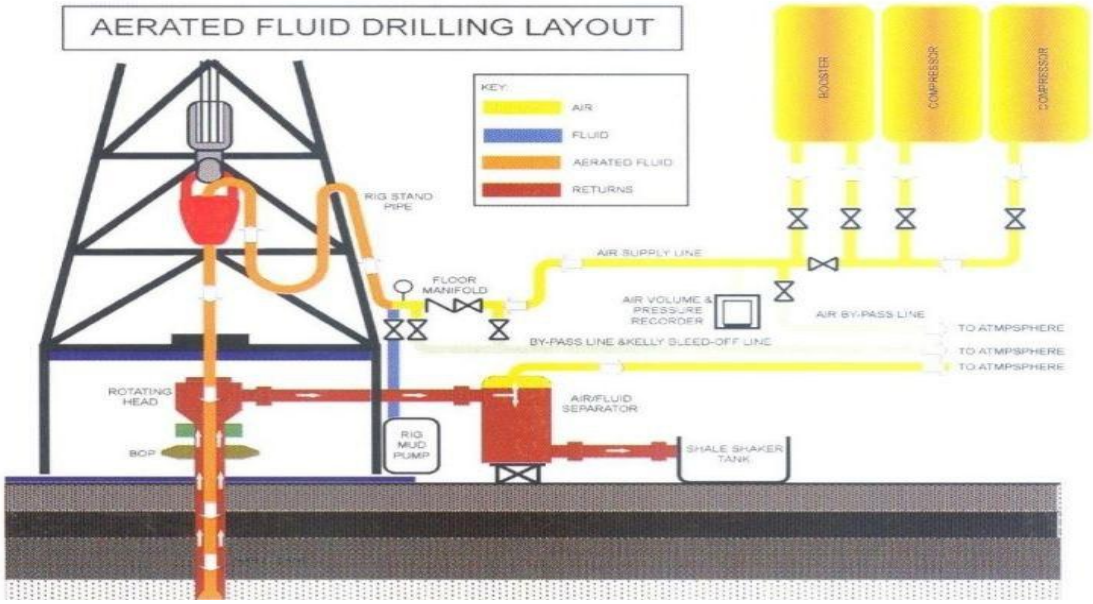


Figure: 3 Air (gas) drilling layout

- The Different Techniques of Injection

Drill pipe Injection :

It injects gas directly into the drillpipe and mixes with the drilling fluid. The final mixing occurs at the drill bit, where pressure is normally high, and gas volume is usually low. This method is straightforward and guarantees that the full volume of gas and liquid is available to clean the wellbore while powering downhole apparatus. Nonetheless, several challenges arise, such as the corrosion from oxygen in the residual gas; the tendency to create pressure surges; the inefficiencies of the horizontal wells in which gas and liquid tend to separate. Moreover, connections take longer since one has to bleed the compressed gas out of the drillpipe, and most effectively, mud pulse MWD systems cannot be used.[6]

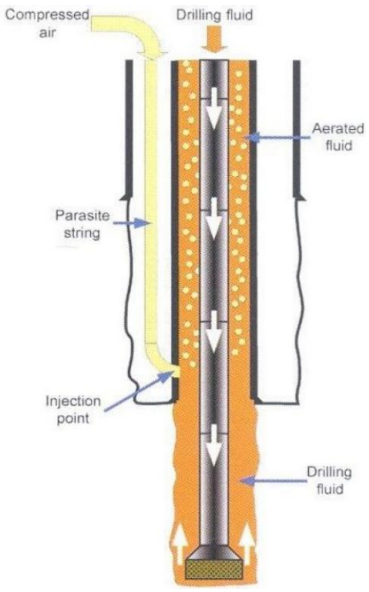
Drill pipe Injection Using a Jet Sub:

A short bit jet sub is inserted into a drill collared section of the drillstring to release gas into the annulus at desired depths. This setup helps to aerate the fluid column during connections and trips, thus greatly reducing pressure surges and preventing lost circulation. The jet sub can be installed without any forethought for a modified drillstring since it is installed within the drill string during drilling. However, it diverts some 20% of circulating fluid from the bit, hence losing some

efficiency. It also faces the same problems inherent to standard drillpipe injection used within a horizontal well and does not work together with mud pulse MWD.[6]

Parasite Tubing String:

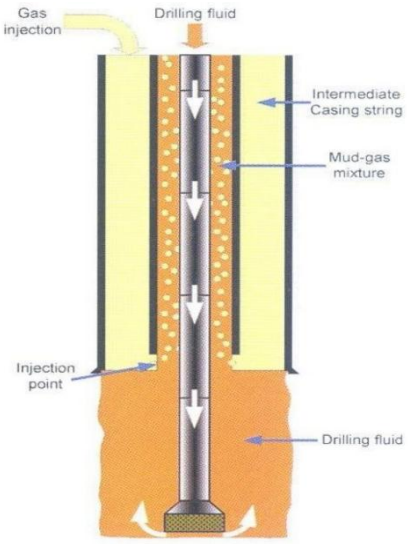
This method employs a small tubing string attached to the casing to inject gas at or near the base of the surface casing. This arrangement aerates the upper section of the well during connections trips, reduces pressure surges, and minimizes oxygen corrosion in the upper wellbore. This parasite string also makes it possible for mud pulse MWD to work; this is a considerable point in its favor. However, the technique will require larger surface holes and wellhead modifications, besides corrupted tubing handling. It also could negatively impact cement quality by shifting the casing. is then placed directly in line with the permanent casing string. Gas injection is carried out between these two strings into the annular space.[13]



Parasite tubing string

Concentric casing string:

In this technique, a dual casing setup is employed, with a secondary lunette or annulus for gas injection in between the inner and outer casings. This allows for continuous gas flow, which can limit surges while making connections and tripping. It permits mud pulse MWD, with the added advantage of being able to reuse the inner casing. Nonetheless, concentric casing requires larger surface holes, specialized wellhead constructions, and some attention to gas management in the secondary annulus in order to avoid surging. Furthermore, the inner casing has torque and pressure design issues.[10]



Concentric casing string

Dual Well System:

This method often associated with drilling for coalbed methane consists of a vertical well sequence with directional laterals. Gas may be injected into the lateral sections from the vertical well to assist drilling. This system becomes attractive to the operator because it fosters gas entry into the wellbore with

simplicity in multiple-lateral production. Great care should still be taken in managing pressure-load in order not to accidentally fall into the situation of wellbore unloading. [10]

Candidate screening and selection for UBD

The uptake of UBD is subject to particular operational problems and formation features. Normally, they are put to work when severe lost circulation or differential sticking emerges during conventional drilling, highly depleted reservoirs that lend themselves to such issues, hard rock formations producing low penetration rates and bit life, and the formation damages, which decreases well productivity. Besides, underbalance drilling allows for sensitive formation productivity evaluations to be made, while drilling is underway. [1]

Indications for Suitability for UBD

Some wells or reservoirs are better suited to UBD than others, primarily by certain important criteria. The foremost element is the minimum drilling fluid density required to be kept to maintain wellbore integrity. Stable rocks can maintain a fluid density less than the pore fluid density without collapsing. Others to consider include:

- Formation Damage Potential: Risks such as clay swelling, fines migration, fluid incompatibilities with rock, phase trapping, bacterial damage, and chemical absorption.
- Lost Circulation Potential: Chance that the fluid will be lost into the formation.
- Stuck Pipe Potential: Risks pending differential or mechanical sticking.
- Hard Drilling Potential: The performance of UBD can vastly enhance penetration rates in dense formations of low permeability and porosity; otherwise, they present a formidable challenge to conventional drilling. [1]

Well-Specific Characteristics

Once a well is pegged as a candidate for UBD, the process evaluation delves into wellbore-specific parameters and details of the conductive fluid used, such as:

- Planned wellbore configuration (vertical or horizontal).

- Diameter of the wellbore.

- Risk of penetrating water-producing zones.

- Possible production of natural gas or sour gas.

- Risk of optimum downhole fires.[1]

Design Process of UBD

To ensure that the technique of UBD selected is the most appropriate one, the design incorporates three fundamental models:

- The optimal circulation rate model: it stabilizes the operation of UBD through proper circulation rates.
- The economic study model: this establishes the economic viability or merit of the selected technique
- The calculation of pressure models serves to affirm wellbore stability, hence maintaining suitable pressure management.
- Creating competent engineers in planning these models will complete the UBD operations in a manner whereby they balance technical feasibility against economic incentives to guarantee successful project delivery.[1]

Good Candidate Indicators for UBD	Bad Candidate Indicators for UBD
Because they have fewer problems with differential sticking and lost circulation, depleted reservoirs with consolidated formations make great UBD prospects.	Poor quality reservoirs. UBD can not make a formation something that it is not.
UBD is most suited for naturally fractured and vugular formations that are prone to fluid losses and sticking problems.	Easy UBD is made possible by high permeability and pore pressure, but same factors can also lead to drawdown, excessive rates, and problems with surface equipment.
since of their enhanced ROP and longer bit life, hard rock formations make great UBD candidates since they are cemented.	Maintaining underbalanced conditions and managing bottomhole pressure are difficult tasks for shallow wells.
UBD is an excellent option for highly permeable formations that are susceptible to differential sticking and lost circulation.	Unstable deposits and swelling shale can lead to wellbore stability problems if they are not balanced.
To lessen formation deterioration, UBD is a useful option for formations with substantial damage or a skin factor of five or above.	Under UBD conditions, formation damage may worsen in formations that are prone to spontaneous imbibition.
Although difficult, wells with	Frequent-trip wells may result

laminated or heterogeneous formations that exhibit different permeabilities and porosities are appropriate for UBD.	in significant fluctuation between overbalanced and underbalanced conditions, which could negate the benefits of UBD and cause harm.
reservoirs with low-medium permeability and high production.	High depletion at the heel due to long UBD intervals may necessitate unfeasible surface equipment.
formations that are sensitive to rock fluids.	Since reservoir pressure is essential for establishing UBD conditions, formations with inadequate reservoir pressure knowledge make UBD design more difficult.
formations that are sensitive to different fluids.	High H_2S wells present serious safety hazards and make system design more difficult.
sections of holes with different pressures.	Reducing wellbore pressure can help control crossflow or unfeasible equipment requirements that may arise from drilling sections with different formation pressures.

Table 1 : good and bad indicators for UBD [1]

UBD Equipment and Rig Modifications Compared to OBD:

- **Rotating Control Device (RCD)**

1. Primary Function

- Unlike traditional blowout preventers (BOPs), the RCD seals on the drill pipe while it may rotate and move vertically.
- In UBD, this device encircles the upper part of the drill string and functions as a seal so that gas, fluids, or cuttings are arrested in travelling out of the borehole and consequently ground-level.[2]

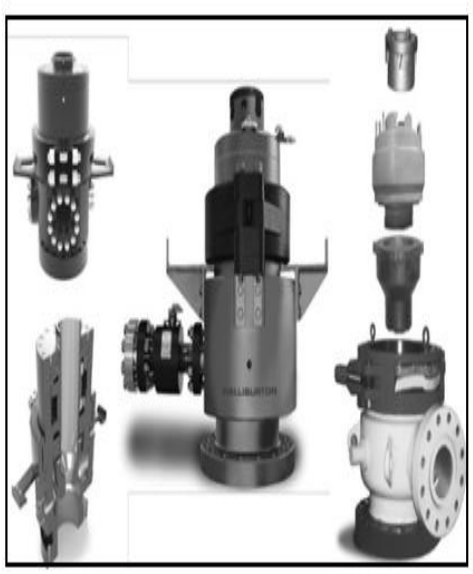


Figure: 4 Rotating Control Device

2. Key Components

❖ Rotating Sealing Element:

- It encircles and rotates with the drill string while providing a pressure-tight seal during operations.
- Usually made with high-strength elastomers designed to resist friction.[2]

❖ Bearing Assembly:

- It supports the rotating element, providing smooth operation under dynamic loading conditions.
- Features internal seals that allow it to operate under high pressure without leaking.[2]

❖ Hydraulic Control Unit:

- Provides hydraulic pressure to operate RCD and to adjust the pressure as necessary.[2]

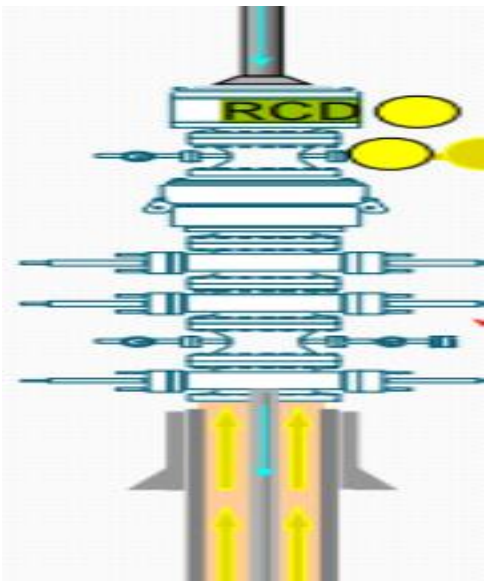


Figure:5 Rotating Control Device

❖ Flowline Connection:

- Allows diverting the flow of wellbore fluids and gases to separation units or choke manifolds for further handling.[2]

3. Technical Specifications

- Maximum Pressure Rating: 10,000 psi (depends on the model).
- Operational Speed: accomodate a rotation speed up to 150 RPM.
- Temperature Resistance: High-temperature rating up to 150°C (302°F).
- Longevity: Designed to withstand harsh drilling environments through special service life treatment.[2]

4. Role in UBD

Pressure Management:

- The RCD allows for closed-loop control of pressure differential across the wellbore and equipment installed on the surface.
- Continual evaluation and management of pressure at the wellbore in real-time.[2]

Fluid and Gas Management:

- Works in conjunction with UBD choke manifolds and separation units to facilitate effective multidimensional flowing of gases and liquids.[2]

Enhanced Safety:

- Greatly decreases kick occurrences, whereby underbalanced fluid is able to maintain control over the wellbore pressure while drilling.[2]

5. Pivotal Aspect of Well Control

- The RCD is pivotal in dealing the permutations of wellbore complexities, such as
- Depleted Reservoirs: Reduces chances of fluid loss to the abyss.
- High-Pressure Zones: Keeps pressure balance to maintain against uncontrolled influxes.
- Horizontal and Directional Wells: Ensures well control in the face of challenging geometries.[2]

6. Challenges:

- **Wear and Maintenance**: Requires regular inspections due to wear on the sealing element.
- **Closing Pressure**: Optimal pressure minimizes wear while maintaining a secure seal.
- **System Dependency**: Requires integration with other pressure control systems.[2]

- **Drill pipe non-return valves (NRV)**

1. **What is an NRV?**

    - The **Non-Return Valve (NRV)** is installed inside the drill pipe string to prevent the backflow of fluids, especially gas, during operations like making connections. It acts as a barrier to stop gas or fluid from flowing the wrong way inside the pipe, ensuring pressure control. [2]

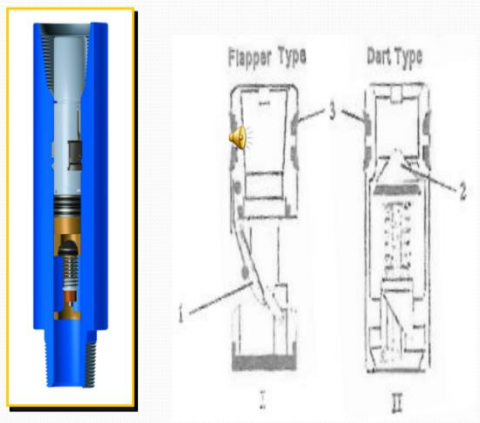


Figure:6 Non-Return Valve

2. **Function in UBD:**

    - In UBD, where drilling fluid is lighter than formation pressure, the NRV prevents upward gas flow and helps maintain well pressure. It also aids in bleeding off excess pressure safely without allowing uncontrolled fluid escape. [2]

3. **Installation:**

    - The NRV is installed within the drill string, typically at regular intervals, to prevent backflow when the drill string is not in use or during operations like making or breaking connections. [2]

4. **Key Benefits:**

    - **Prevents Backflow**: Stops formation fluids from flowing back up the string, preventing pressure loss or blowouts.
    - **Improves Safety**: Plays a role in well control, especially during critical UBD stages.
    - **Enhances Efficiency**: Improves pressure management and wellbore control. [2]

5. **Associated Equipment in UBD:**

    - Works alongside tools like the **Rotating Control Device (RCD)**, **Choke and Manifold System**, and **Gas Detection Systems**. [2]

- Choke and manifold system

1. **Function in UBD:**
    - In UBD, pressure is intentionally kept lower than the formation pressure. The choke manifold helps prevent overpressure by controlling fluid and gas flow, allowing for real-time adjustments.[2]

Figure:7 Choke manifold system

2. **Key Components:**
    - **Isolation Valves**: Separate different flow paths.
    - **Chokes**: Regulate fluid and gas flow to control pressure.
    - **Bleed-off Valves**: Release excess pressure safely.
    - **Pressure Measurement Points**: Monitor pressure levels.[2]
3. **Benefits:**
    - **Pressure Control**: Maintains safe wellbore pressure, reducing blowout risks.
    - **Improved Safety**: Prevents uncontrolled fluid escapes and helps with well control.
    - **Efficiency**: Allows easy replacement or repair of chokes without shutting in the well.[2]
4. **Associated Equipment:**
    - Works with tools like the **Rotating Control Device (RCD)**, **Gas Detection Systems**, and **Non-Return Valves (NRVs)**.[2]
5. **Advanced Technology:**
    - Features remotely controlled chokes and ongoing improvements to enhance efficiency, reduce size, and automate functions.[2]

- Separator system

1. **What is the Separator System?**
    - The Separator System divides the returned flow into four phases:
        - **Heavy Liquids**: Mud and water.
        - **Light Liquids**: Oil and condensate.
        - **Gas**: Natural gas.
        - **Solids/Cuttings**: Debris from the drilling process.[2]

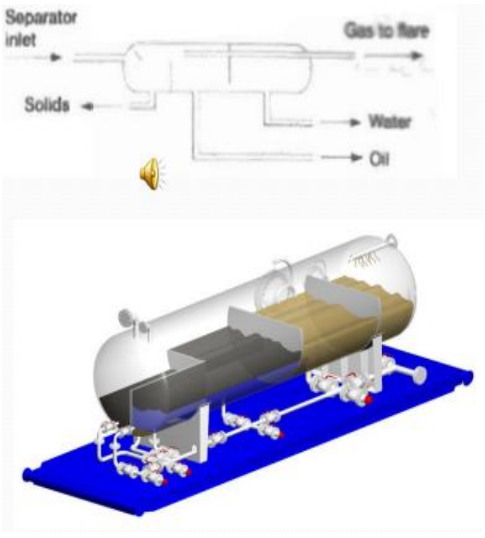


Figure:8 Separator

2. **Types of Separators:**
    - **Vertical Separators**: Used for high gas flow.
    - **Horizontal Separators**: Used to separate fluids with varying densities, such as oil and water.[2]
3. **Factors Affecting Separator Design:**
    - **Drilling Environment**: Onshore vs. offshore.
    - **Type of Drilling Fluid**: Mud properties influence separator choice.
    - **Well Parameters**: Well diameter, depth, and expected production rates affect design.
    - Typically, four-phase separators are used to handle oil, gas, water, and solids.[2]
4. **Function in UBD Operations:**
    - **Separating Return Flow**: Efficiently separates gas, liquids, and solids.
    - **Handling Gas**: Manages gas by discharging it, treating it, or reinjecting it into the well.
    - **Ensuring Safe Flow**: Proper separation enhances safety and operational efficiency.[2]
5. **Additional Equipment in UBD:**
    - **Air Compressors & Boosters**: Regulate air or gas flow.
    - **Nitrogen Generators**: For nitrogen injection.
    - **Mud Treating Equipment**: To treat and recycle fluids.
    - **Down-hole Casing NRVs**: Prevent backflow up the drill string.
    - **Gas Detection Systems**: Monitor for gas leaks or changes in gas composition.[2]
6. **Importance of the Separator System:**
    - **Pressure Management**: Helps control wellbore pressure below formation pressure.
    - **Safety**: Proper separation prevents blowouts, unwanted fluid flow, and pressure buildup.
    - **Environmental Protection**: Minimizes environmental impact by managing gas and fluids properly.[2]

- Flare system

Key Functions:

- **Burning Excess Gas**: The flare system ensures that gas returned with drilling fluids or produced from the formation is safely burned, preventing dangerous gas buildup.
- **Safety Mechanism:** It provides controlled combustion, reducing fire risks in other parts of the operation.[2]

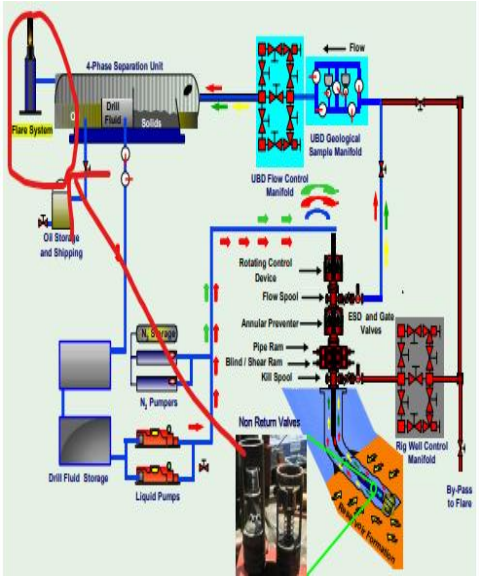


Figure:9 flare system

Components:

- **Flare Stack:** The vertical pipe where the gas is burned off.
- Liquid Seal Drums: Prevent flame propagation back into the flare system.
- **Screen Flame Arresters:** Prevent flames from traveling through the system.
- **Nitrogen Injection:** Used to suppress the flare when gas volumes are low, ensuring ignition only when sufficient hydrocarbon gas is present.[2]

Types of Gas Handled:

- **Natural Gas:** Typically methane produced during drilling.
- **Other Gases:** Including nitrogen or air, safely vented or burned off.[2]

Challenges and Improvements:

- **Efficiency**: Modern flare systems achieve over 98% combustion efficiency, **reducing harmful emissions.**
- **Emissions Control**: New technologies ensure compliance with environmental standards, minimizing pollutants, smoke, noise, and odors.
- **Safety:** Continuous improvements focus on enhancing safety and reducing risks associated with gas handling.[2]

Importance in UBD:

- **Safety & Pressure Control:** The flare system helps prevent pressure buildup by burning off excess gas.
- **Environmental Responsibility:** Proper management of produced gases minimizes environmental hazards.
- **Efficient Gas Management:** The system ensures smooth operations by safely managing and burning off excess gas.[2]

• Surface valves and piping

1. Surface Safety Valve (SSV)

- **Definition:** A hydraulically or pneumatically operated valve between the wellhead and choke manifold, acting as a safety barrier for emergencies.[2]

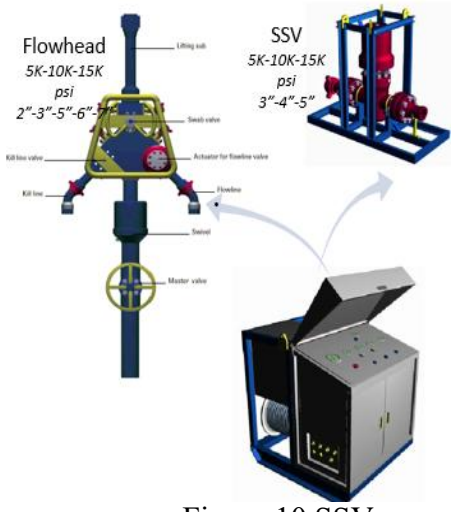


Figure:10 SSV

- **Purpose**: Protects equipment, isolates the well during overpressure, leaks, or high flow, especially in hazardous wells (e.g., with H_2S).[2]
- **Operation**:
    - Integrated with an Emergency Shut Down (ESD) system.
    - Modes: Automatic (triggered by unsafe conditions) and Manual (for planned or emergency use).
    - Alarms notify operators of activation or failures.[2]

2. Functionality

- **Flow Control**: Regulates and prevents backflow of drilling fluids and gases.
- **Pressure Management**: Maintains safe pressure in conjunction with the choke system.
- **Emergency Isolation**: Quickly isolates the well during abnormal conditions.[2]

3. Key Components

- **Valves**: Includes SSVs, check valves (NRVs), and control valves.
- **Piping**: High-pressure, corrosion-resistant, suitable for harsh conditions like H_2S.
- **Instrumentation**: Monitors pressure and flow, integrated with automated controls.[2]

4. Importance

- **Safety**: Reduces accident risks.
- **Efficiency**: Enables continuous and controlled fluid circulation.
- **Environmental Protection**: Prevents hydrocarbon release.[2]

5. Challenges

- Requires regular maintenance to prevent failures.
- Needs robust manual overrides for automatic system reliability.
- Must be compatible with HPHT and corrosive conditions.

By integrating surface valves and piping into UBD systems, operators achieve enhanced safety, operational efficiency, and environmental compliance.[2]

Rig Modifications

1. Underbalanced Drilling (UBD):

- **Requires modifications** to handle gas flow, including:
    - Adding separators for gas-liquid separation.
    - Enhancing pressure control systems to ensure safe operations.[2]

2. Overbalanced Drilling (OBD):

- **Minimal modifications required** as conventional rigs are sufficient.
- Relies on simpler mud circulation systems compared to UBD setups.[2]

Case study:

Saudi Aramco introduced underbalanced drilling (UBD) in the Ghawar field to reduce formation damage, eliminate acid stimulation, and improve injection rates. UBD significantly increased the rate of penetration (ROP), reducing costs and drill time.[14]

Background:

PWI wells in the Arab-D reservoir were traditionally drilled overbalanced, inciting formation damage and operational issues like stuck pipe and lost circulation. UBD applied water as a drilling medium and minimized these woes by maintaining an underbalanced condition throughout the reservoir.[14]

Planning:

UBD was utilized on PWI wells with varying porosity zones. With a drawdown of 200 psi at the bit, underbalanced conditions were established, while flow rates of 180–250 gpm were maintained to achieve hole clearing and system efficiency. An elaborate engineering and operational envelope ensured the winds of success blew favorably.[14]

Training:

Extensive training, including IADC certification, was provided to selected human resources, so that efficient and safe UBD operations could be instituted.[14]

Introduction of initial wells:

The initial three UBD wells were beset with some bumps in the road due to equipment selection and well design not being integrated. Confusion with multiple service providers and dual laterals not getting isolated were issues that resulted in lost circulation due to overbalanced conditions and poor hole cleaning. The other interruptions were due to sour gas blowback from waste pits and logistical problems with water-handling operations.[14]

Casing-point Change:

At first, the 7-inch liner was set 2 ft below Zone 2A, hence placing Zone 2A underbalanced and Zone 2B overbalanced. Later wells isolated Zone 2A by setting a casing point 2 ft below Zone 2B. This optimized UBD operations and resolved drilling issues.[14]

Change in Laterals:

The dual-lateral wells were redone into single-laterals with reduced lengths. This ensured less rig time, lesser fluid production, while at least having or exceeding the injectivity targets.[14]

Change in Wellpath:

Wellpaths were smoothed to reduce tortuosity, which meant increased drilling efficiency, reduced fluid production, and minimized storage needs. [14]

Documentation:

New Operational Procedures and Equipment Manuals were developed for UBD in Saudi Aramco in many aspects such as equipment, health, safety, and environment management, well control, snubbing operations.[14]

Sour Gas Provisions:

H_2S management guidelines included pre-startup checklists and safety measures to minimize sour gas risks in different kinds of wells.[14]

Subsequent Wells:

Better equipment integration and HSE planning allowed for successful drilling of ten more wells with minor challenges in the drilling. This was a learning approach for both Saudi Aramco and the service providers.[14]

Conventional VS UBD Comparisons:

Comparisons of conventional and underbalanced drilling (UBD) wells in the Ghawar field show considerable differences:

Drilling Fluid Costs:

In UBD wells, produced formation water including caustic reduced downhole pressures, hence the use of expensive conventional drilling mud and acid cleanups weren't necessary and saved a lot of money.[14]

Bit Life:

For long laterals, conventional wells would use more than two bits with an average of 653 ft of life per bit. Comparatively, UBD wells could use one bit with an average life of 3,163 ft, thus saving on tripping time and bit costs.[14]

Rate of Penetration (ROP):

UBD wells achieve ROP on average over three times higher than that in conventional wells, due to the lower bottom-hole circulating pressures and more effective cuttings removal. Consequently, this produced significant rig time savings and led to improved operational efficiency.[14]

Injectivity Index:

UBD, wells achieved an injectivity rate that was two times better than conventional wells, even with shorter laterals, significantly improving reservoir performance.[14]

Initial Well Challenges:

The first well in the UBD campaign was confronted with a myriad of challenges, chief among them standpipe pressure that was very high, scale in the BHA, and sliding difficulties. Operations to free the stuck pipe complicated matters greatly, as there were several cases of pipe backing off leading to very high flowback. Thus, after 30 days, it was found that injectivity was almost like that of wells in conventional constructions. Modifications and delays leading to unnecessary costs could rather have been avoided had reservoir well design been optimized with early injectivity testing.[14]

Challenges with well 2:

At 6,920 ft, the 7- in. casing stuck, and various attempts to free it were unsuccessful. The well was sidetracked, and it was indeed determined that the

isolation valve should not be incorporated in this section since the failure was due to increased casing outer diameter difficulties.[14]

Challenges with Well 3:

On the third well, there was progress, with the hole drilled and opened up to 9-7/8 in. The 7- in. casing with the isolation valve was run, but there were various failed attempts at engaging and opening it, which led to the valve needing milling.[14]

Challenges with Well 4:

The running of the 7- in. tie-back string and isolation valve was initially successful on the fourth well. Still, right upon completion, the valve was unable to hold pressure for a short while, possibly due to some obstruction to the flapper valve.[14]

Recent Well Success:

A recent well was drilled with a 3,235 ft horizontal completion in only 53 hours with one bit run. The well was kept in good underbalance and under satisfactory inflow at all times to achieve the highest injectivity in the campaign with a single brine kill.[14]

Early Isolation Valve Experiences:

To maintain underbalanced conditions during drilling operations, mechanical or hydraulic down-hole isolation valves were tested as alternatives to snubbing units, wherein these valves would isolate the formation while tripping out of the hole so that the drillstring would either be pulled up or put back down without killing the well. Valves enable safer and faster tripping, thus reducing rig time and improving safety. The advantages included not needing a snubbing unit, faster tripping, and a safer means of deploying completion tools. [14]

Mechanically Operated Isolation Tool:

A mechanically operated isolation valve using a flapper valve and metal-to-metal seals was tested. However, when the bent housing bottom hole assembly was

inserted into the tool, some problems occurred that could destroy the assembly but did not require any external control lines.[14]

Hydraulically Operated Isolation Tool:

A hydraulically operated isolation valve, requiring two control lines, was tested in a later well. The valve worked with a minimal number of issues, showcasing its potential for becoming a viable solution to do away with a hydraulic workover unit.[14]

Operational Improvements:

A step-by-step method of enhancing the technology of UBD continuously modified operations, each well incorporating experiences gained. Close teamwork, sound decision-making from management, and thorough audit of equipment were all crucial in ensuring this project's success.[14]

Lessons Learned:

The UBD method was safe with an increase in ROP and bit life and reduced formation damage. The right equipment selection and a single service provider for UBD equipment generated improved operations. Safety, health, and environmental procedures were strictly followed, including safety from H2S and enhanced waste pit systems. Data acquisition enhanced the operation and lead to greater insight into the reservoir.[14]

Advantages of UBD over OBD:

Operational Benefits

- UBD (Underbalanced Drilling)

1. Faster Drilling Rates:

UBD allows for faster penetration rates because the reduced bottom-hole pressure decreases the energy required to break the rock. With less resistance, drill bits work better and therefore spend less time on the rig.[1]

2. Lower Stuck Pipe Incidents:

In UBD, the pressure in the wellbore is below formation pressure, reducing differential sticking. This minimizes instances of the drill string getting stuck in the wellbore, a common challenge in overbalanced conditions where mud forces interact with the formation walls.[1]

- OBD (Overbalanced Drilling)

1. Enhanced Well Control:

The application of high-density drilling fluids in OBD prevents formation fluids from entering the wellbore. This offers good well control, specifically in high-pressure reservoirs, and thus OBD is considered safer in this kind of environment.[2]

2. Simpler Operational Setup:

OBD depends upon developed machinery and methods such as mud circulation systems and blowout preventers. It is more widely understood within the industry and less complicated to use commercially than UBD, which demands specialized equipment and training.[1][12]

Reservoir Benefits

- UBD (Underbalanced Drilling)

1. Minimal Invasion of Drilling Fluids :

UBD prevents the drilling fluids from entering the reservoir by keeping the wellbore pressure lower than the formation pressure. This maintains reservoir permeability and porosity to avoid obstructing the natural flow of hydrocarbons from the reservoir. [2]

2. Early Production Testing :

UBD allows the reservoir to flow to the surface during drilling, enabling real-time tests of the reservoir fluids (oil, gas, or water) and providing important data about the characterization of the reservoir for further decision-making while drilling. [12][14]

- OBD (Overbalanced Drilling)

1. Higher Chances of Formation Damage:

In OBD, the greater wellbore pressure drives mud into the reservoir pores, a process that may block pathways and reduce permeability. The wellbore damage caused by this usually necessitates expensive stimulation techniques like acidizing or fracturing to restore well productivity. [1]

Economic Benefits

- UBD (Underbalanced Drilling)

1. Reduced Remediation Costs:

UBD minimizes formation damage, thus reducing the need for remediation post-drilling. A lot of cost savings come from avoiding stimulation of wells, cleanup, and enhanced recovery efforts.[1][12]

2. increased Reservoir Productivity:

Ability for UBD to preserve reservoir integrity leads to higher production rates over the well's life. While initial investments in UBD equipment and training may be higher, long-term benefits often offset the upfront costs.[2][14]

- OBD (Overbalanced Drilling)

1. Lower Initial Costs:

OBD uses less complicated, more traditional equipment such as mud pumps, tanks, and blowout preventers. Consequently, capital investment is considerably lower than with UBD, which requires specialized equipment including RCDs and real-time monitoring systems. [1]

2. Potential Long-Term Productivity Loss:

The invasion of fluids into the formation in OBD can cause damage, leading to reduced rates and increasing costs of stimulation in wells. Over time, this will impair the economic efficiency of OBD, especially in sensitive reservoirs.[2]

Challenges of UBD vs OBD

1. Pressure Instability

- UBD (Underbalanced Drilling):

Sustaining underbalanced conditions during operations requires very rigorous pressure management. Variation in formation-pressure or gas-injection rates may lead to wellbore instability and instabilities such as kicks or blowouts. Such problems can be avoided only with continuous real-time monitoring.[7][9]

- OBD (Overbalanced Drilling):

Surges in pressure due to the use of high-density fluids may cause wellbore instability. Mud losses into the formation may occur due to excessive pressure, perhaps even fracturing the formation, which again would require costly remediation measures to restore well integrity.[2][17]

1. Environmental and Safety Shortcomings

- UBD (Underbalanced Drilling):

The introduction of potentially explosive gases such as nitrogen and air-or also by natural gas- carries considerable safety hazards including three of the most catastrophic problems: downhole fire, well blowouts, and explosions. Some of these problems can be mitigated through proper handling and venting while a proper monitoring system must be in place during UBD operations to ensure the safety of the workers and operations.[7]

- OBD (Overbalanced Drilling):

Generally, OBD tends to have a greater environmental impact because it requires the disposal of large amounts of oils, lubricants, and any contaminated cuttings. The encroaching mud may become contaminated and thus might contribute to contam ination of the groundwater, wider environmental degradation, declines in agriculture, and social confrontation.[2]

1. Equipment Challenges

- UBD (Underbalanced Drilling):

UBD operations employ very highly sophisticated and costly equipment, such as rotating controllers (RCDs), compressors, or multiphase separators. This requires a higher skill level for operating and maintaining such tools, thereby adding to the complexity of UBD sets and increasing their cost.[7]

- OBD(Overbalanced Drilling):

Equipment-wise, OBD is straightforward (for example, mud pumps, tanks, blowout preventers); its major limitation is it cannot be adapted for the dynamic conditions of

the reservoir. Furthermore, the pressure application varies from one completely drilled fragment to another within the same area, hence drilling through fractured or depleted zones using dense mud could require an extensive amount of time, which is detrimental to the effectiveness of operations.[2]

Innovations in Drilling Technology: UBD vs. OBD

Real-Time Monitoring Systems:

UBD: Real-time monitoring systems are integral to maintaining underbalanced conditions, allowing precise pressure control and improving safety during operations.

OBD: While OBD also uses real-time monitoring, it primarily focuses on preventing well control incidents caused by overbalanced conditions, such as kicks or blowouts.[17][20]

Improved Pressure Control Systems:

UBD: Advanced managed pressure systems help maintain delicate pressure balances in depleted or fractured reservoirs, minimizing formation damage.

OBD: OBD relies on simpler pressure control systems but faces challenges with fluid losses and formation damage in certain reservoirs.[10][12]

Specialized Equipment:

UBD: Innovations like rotating control devices (RCDs) and multiphase separators enhance operational flexibility and accuracy.

OBD: While OBD equipment is less complex, it lacks adaptability for dynamic reservoir conditions, relying heavily on heavy mud systems for pressure management.[1][12]

Integration of UBD and MPD vs. OBD Practices

- UBD and Managed Pressure Drilling (MPD):

Integration between UBD and MPD offers the following advantages:

- Enhanced Precision: Real-time pressure adjustments optimize wellbore stability, reducing operational risks.

- Safer Operations: Combined systems ensure better control over pressure fluctuations, especially in depleted or fractured formations.

- Reservoir Productivity: The integration allows for reduced formation damage, leading to better long-term productivity.[1][10]

- OBD Practices:

OBD, while not typically integrated with MPD, depends on high-density drilling fluids for pressure control. This makes it effective in high-pressure reservoirs but less efficient in minimizing formation damage or adapting to dynamic reservoir conditions.[1]

Emerging Trends in Automation and Digital Monitoring: UBD vs. OBD

Automation:

UBD: Automation is increasingly used in UBD to manage complex operations, including AI-powered decision-making and automated pressure controls. These technologies improve operational efficiency and reduce the need for manual intervention.

OBD: Automation in OBD is focused on safety mechanisms, such as blowout preventers and mud circulation systems, but lacks the predictive analytics capabilities that are common in UBD.[9][20]

Digital Monitoring:

UBD: Advanced monitoring tools provide real-time data, enabling dynamic adjustments to pressure and flow rates. This enhances well productivity and safety.

OBD: While OBD benefits from digital monitoring for well control, its simpler operational requirements mean less reliance on cutting-edge data analytics.[2][17]

Future Developments in UBD vs. OBD

Digital Technologies:

UBD: Continued advancements in machine learning and data analytics will further enhance reservoir understanding and decision-making capabilities.

OBD: Improvements will likely focus on refining existing systems to better handle high-pressure formations and reduce operational risks.[9][20]

Sustainability:

UBD: UBD’s minimal environmental footprint aligns with the industry's shift towards sustainable practices, including reducing carbon emissions and optimizing resource use.

OBD: OBD’s reliance on heavy mud systems increases waste and environmental impact, making it less sustainable compared to UBD.[1][2]

Equipment and Safety Innovations:

UBD: Future designs will focus on advanced tools for pressure control, gas injection, and real-time monitoring to further enhance operational safety and efficiency.

OBD: Innovations will focus on enhancing mud systems and blowout preventers to improve well control and mitigate formation damage.[18]

General Conclusion

UBD has redefined modern drilling practices through its immense promise of preserving reservoir integrity against formation damage while increasing production. These newer techniques include gas injection, foam systems, and precise pressure control mechanisms, thus proving most effective in fractured and depleted reservoir drilling. On the other hand, they often require high-tech equipment capable of managing accurate pressure with higher initial investments.[2]

As a conventionally used method that is widely employed in high-pressure and stable formations, though simpler in regards to its setting up and operation, OBD is more often rule-deprived and formation damaging enough to reduce productivity; it may oftentimes involve costly restoration efforts.[12]

Though further clerked to overcome UBD limitations and assisting its revised application, incorporating higher technologies, goal monitoring, and MPD is nothing but the last nail in the coffin of these limitations. As sustainability and efficiency seem to be focused on by the oil industry, the future of UBD seems to lie more on its quality of being able to contend with expediency in all forms of operations over environment-friendly measures.

Bibliography

[1] Rehm, B., Haghshenas, A., Paknejad, A. S., Al-Yami, A., & Hughes, J. (2013). Underbalanced drilling: Limits and extremes. Gulf Publishing Company.

[2] Bourgoyne, A. T., Millheim, K. K., & Chenevert, M. E. (2007). Applied drilling engineering (2nd ed.). PennWell Books.

[3] Gao, D., & Gray, D. (2012). Design and performance of aerated fluids in underbalanced drilling operations. Journal of Petroleum Science and Engineering, 86(1), 58-65. https://doi.org/10.1016/j.petrol.2012.04.013

[4] Bennion, D. B., & Thomas, F. B. (1994). The use of foam-based fluids in underbalanced drilling. SPE Drilling & Completion, 9(2), 139-145. https://doi.org/10.2118/21178-PA

[5] Chenevert, M. E., & Sharma, A. (2001). Foam and gas injection for underbalanced drilling operations. SPE/IADC Drilling Conference, 1-9. https://doi.org/10.2118/74207-MS

[6] Mitchell, R., & Miska, S. (2009). Enhancing wellbore cleaning using drillpipe injection in UBD operations. OnePetro. https://doi.org/10.2118/121345-MS

[7] Rehm, B., & Mathis, R. G. (2010). Gasified fluids in underbalanced drilling: Stability challenges and solutions. OnePetro. https://www.onepetro.org (https://www.onepetro.org/)

(8 Wilson, D., & Clark, M. (2001). Selection of drilling fluids for underbalanced operations. SPE/IADC Drilling Conference, 1-10. https://doi.org/10.2118/74523-MS

[9] Rehm, B., & Paknejad, A. S. (2010). Hydraulic isolation tools for underbalanced drilling operations. SPE/IADC Drilling Conference. https://doi.org/10.2118/122929-MS

[10] Rehm, B., & Mathis, R. G. (2011). The application of concentric casing for continuous gas injection in UBD operations. OnePetro. https://www.onepetro.org (https://www.onepetro.org/)

[11] Rehm, B., & Mathis, R. G. (2010). Hydraulic isolation and valve technology for underbalanced drilling: A comprehensive approach to well control. SPE/IADC Drilling Conference.

[12] SPE 150056 (2012). Optimizing underbalanced drilling for cost efficiency and improved bit life in complex reservoirs. SPE/IADC Drilling Conference.

[13] Rehm, B., & Mathis, R. G. (2011). Advances in hydraulic isolation tools for underbalanced drilling. OnePetro. https://www.onepetro.org (https://www.onepetro.org/)

[14] Al-Yami, A., & Hughes, J. (2014). Optimizing UBD techniques in the Ghawar field: A Saudi Aramco case study. Middle East Oil Journal, 234(5), 88-92.

[15] SPE 74523 (2001). Mist drilling and its limitations in deepwater applications. SPE/IADC Drilling Conference.

[16] SPE 169847 (2014). Underbalanced drilling applications in depleted reservoirs. SPE/IADC Drilling Conference.

[17] Rehm, B., & Miska, S. Z. (2012). Real-time monitoring and its impact on UBD success: A lessons learned approach. Journal of Petroleum Technology, 64(9), 85-91. https://doi.org/10.2118/167951-JPT

[18] SPE 120349 (2009). Risks and safety measures in underbalanced drilling operations: Focus on H_2S management. SPE/IADC Drilling Conference.

[19] Al-Yami, A., & Hughes, J. (2014). Application of data-driven decision-making in underbalanced drilling: A case study from the Ghawar field. Middle East Oil Journal, 234(7), 102-106.

[20] SPE 150056 (2012). The role of data acquisition in improving UBD operations: A case study from offshore fields. SPE/IADC Drilling Conferenc